Title : Evaluation of Geometric Elements and Speeds using Probability Theory

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Abstract

Safety based highway geometric improvement is one of the major concerns of road agencies and road designers. Sometimes the significance of the improvement is evaluated based on accident frequencies or complicated performance considerations.
This paper provides a new way of evaluation of the significance of the improvement using probability characteristics of highway design and operational elements. These elements include design speeds and operational speeds. This paper would like to combine mathematically these elements and evaluate specific roadway locations. This type of approach would serve to quantification of existing highway geometric deficiencies.

1. Demand vs capacity

Traffic accidents consist of elements associated with ability or serviceability of drivers, vehicles, and roadways. These elements independently or together affect the accident frequency or even severity. Generally, the adequacy in terms of safety under a specific roadway condition is generally determined by evaluating the elements which could be regarded as ability of the roadway to reconcile with drivers speeding patterns.
Therefore, clear designation of the specific service or drivers' ability based on road conditions is required for evaluating the level of adequacy of the conditions. The conditions independently or together could be called "capacity" in terms of accident likelihood. Drivers' desirability may be the counterpart of the serviceability of road conditions then this may be called demand. In the present paper, the demand and capacity model is introduced to explain the drivers' ability and roadways' serviceability together.

Conventionally, demand and capacity model has been characterized by a ratio of capacity over demand representing the value of the ratio is the status of safety/factor of safety in civil engineering or "reliability" in more diversified terms.
The capacity and demand model is generally expressed in their own performances.

Therefore, demand and capacity model is generally could be regarded as a function of various performances. Examples of the capacity and demand model are commonplace in diversifed spheres. The table below shows the cases of the demand and capacity model.

Table 1 diversified cases of demand and capacity model.

performance	**demand**	**capacity**	**If demand>capacity**
Airplanes' Runaway speed	speed for lift	airplanes' runaway speed	Crash or no lift
Queue length at bus stop	real buses in queue	# of bus stop bay	overflow
# of vehicles/lane	Volume	capacity/lane	congestion
# of customers in restaurant	In coming rate of customer	# of seats	Reduction of sales

How to express the demand and capacity model is one of complicated issues. This is because multiple types of data sets or performances exist in the world and algorithms which may represent these data sets or performances are very limited. Sometimes simple value types of performances are enough for the explanation of the model and sometimes group types are better.

Two definitions are prevalent in representing the model. The performance being observed or obtained as one value, it can be expressed as a deterministic value. On the other hand, the performance being expressed or provided by the type of probabilistic values or distributions, it can be expressed as probabilistic.

In deterministic fields, all comparisons of demand and capacity are undertaken in the type of comparison of deterministic values. The representing types of deterministic values are averages or median because generally it could be said that these values are adequate for representing the whole population. In this case of the model, if demand equals capacity, it is assumed that there are no problems and exists the equilibrium between demand and capacity.

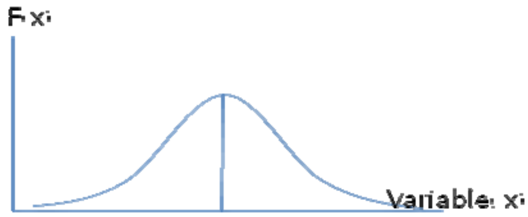
Fig 1 capacity and demand in deterministic or probabilistic field

Deterministic field

If demand = capacity : OK

Probabilistic field

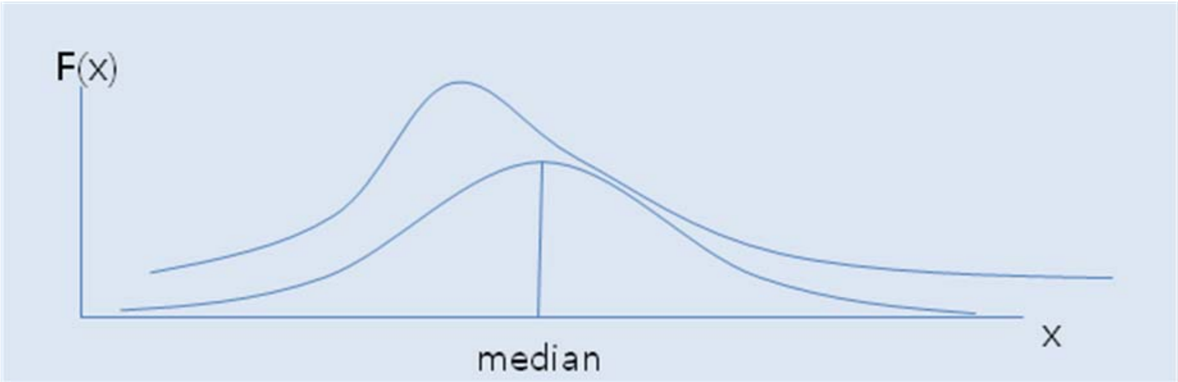
if demand = capacity : NOT OK



On the other hand, in probabilistic fields, pairs of demand and capacity are compared based on probabilistic values. The representing characteristics here are types of distributions and their variances well as averages or medians. Types of distribution and their variances could be said that they are more accurate values for representing the whole population than averages or medians because they infer probabilistic chances of diversified events. Under the probabilistic model, if demand equals capacity, it could be assumed that the relationship is not resolved yet and characteristics of distribution types and their variances should be considered to find out possibility of randomized failures of the probabilistic variables. Therefore, probabilistic research can be regarded more diversified and more conservative than deterministic research.

However, probabilistic research is not easy because of the amount of data collection and tough processes and assumption of data characteristics or distributions.

Fig 2 Diversified distributions of Probability variable



If one distribution of data set follows one typical distribution, the probabilistic research becomes more convenient. More detailed, if a measured distribution can be represented by a mathematical distribution, the measured distribution can be said to have similar attributes and hence greater knowledge of the measured distribution can be inferred. (May, 1990). In more popular and typical distributions such as normal

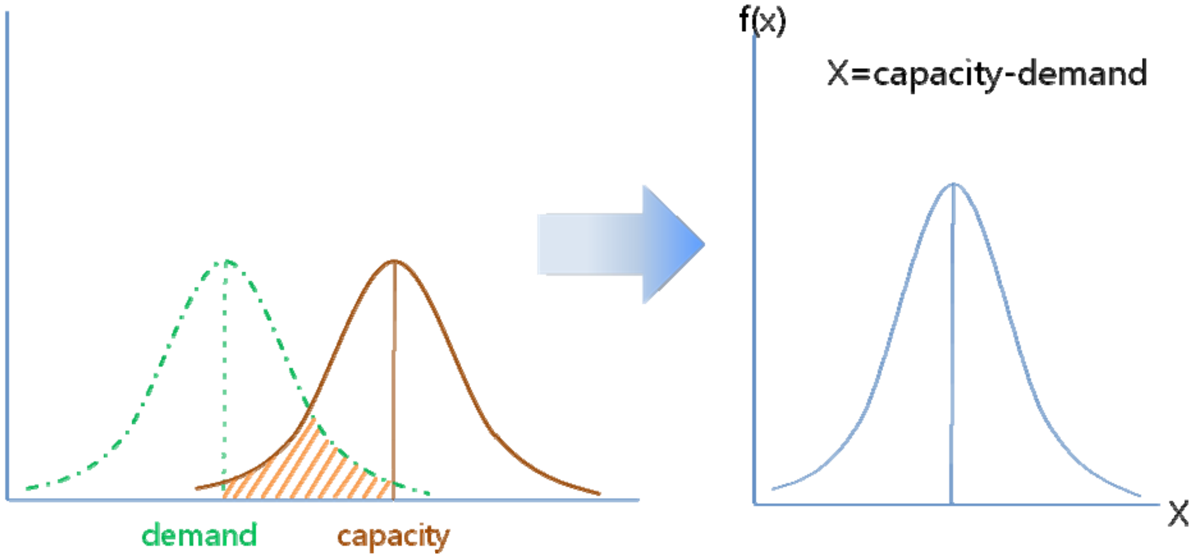
distributions, more easy inference is possible because a typical distribution has easily accessible and understandable statistical characteristics.

Fig 2 shows two types of distributions, that is, one is irregular and asymmetric and the other is a symmetric normal distribution. The normal distribution is one of the most popular probabilistic distributions of which characteristics are easily obtainable in statistical books. The central limit theorem provides conditions and the means to assume one distribution as normal.

2. Distribution of Capacity and Demand

As each of capacity or demand could be simplified into normal distributions, the capacity and demand together could be merged into one distribution. This makes it possible the whole system with various variables is handled in a simplified way as much as the system with characteristic of one variable. Fig 3 shows the way of merging two distributions. Here, the probability variable X represents the variable that capacity minus demand.

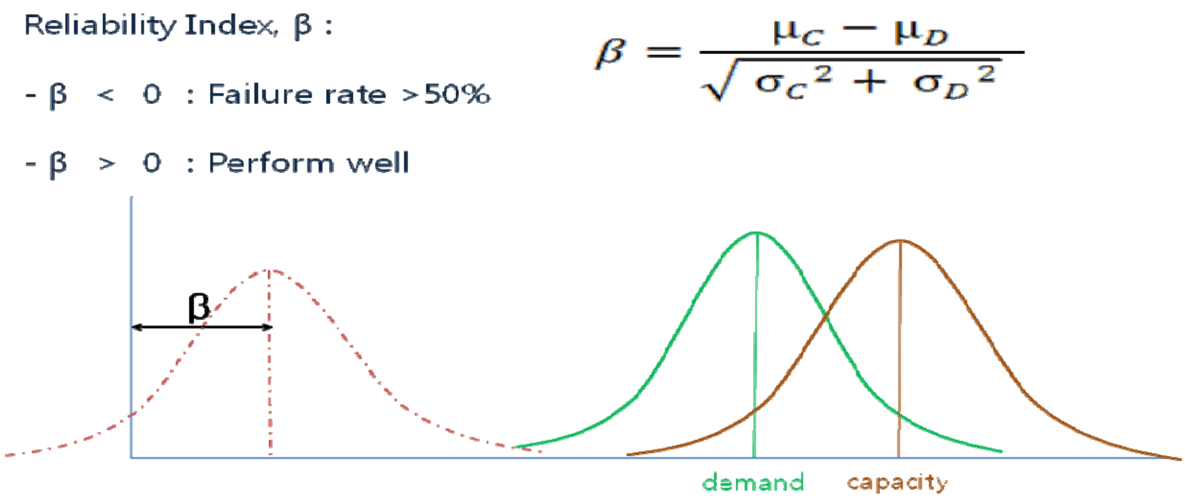
Fig 3 Simple way of merging two distributions



As the variable X is expressed as capacity and demand ratio, this one is easily extended to the concept of the reliability index (Harr, 1996). The index is generally expressed as β, of which the general meaning is z-score of the difference of demand and capacity.

Hence the index represents the probabilistic variation of the margin between capacity and demand. Now the reliability provides more convenient probability scales based on averages and variances of multiple variables. Fig 4 is trying to explain the concept of probabilistic reliability index.

Fig 4 Use of probabilistic reliability index



3. Probability characteristics of highway design and operational elements

Watters and O'Mahony (2007) shows diversified and wide value distributions over elements of traffic accidents such as traffic speeds, curve lengths, deflection angles, and pave widths in specific highway sections. These data also shows the huge gaps of elements highway by highway. More specifically, for the N52 road, Watters and O'Mahony shows that geometric consistency is correlated with accident rates.

Table 2 Relationship between geometric consistency and operating speeds. (Watters and O'Mahony, 2007)

	Watters and O'Mahony (2007)			Dell'Acqua et al. (2007)			Hashim and Bird (2005)			Kanellaidis et al. (1990)	
Location	Ireland			Italy			UK			Greece	
Road	N52			SP312, SP30b, SP52			-			-	
Value	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*	*Min*	*Max*
Operating Speed (km/hr)	75.7	48.2	104.8	84.0	76	98	87.4	67.6	105.9	51	116
Curve Radius (m)	235.2	48.4	514.9	587.9	25	5000	410.4	108.1	931.6	50	1100
Curve Length (m)	120.4	18.9	321	89.6	33	256	196.4	39.7	795.5	-	-
Deflection Angle (deg.)	43.9	3.5	111.8	31.7	1.7	118.5	31.3	7.2	78.4	-	-
Paved Width (m)	6.9	6	10.1				8	6	9.6	-	-
Distance Between Edgelines (m)	6.4	5.7	9	6.4	5	10	7.5	6	9.4	-	-
Lane Width (m)	-	-	-	-	-	-	-	-	-	3.5	3.8
Shoulder Width (m)	-	-	-	-	-	-	-	-	-	0	2.5

Operational observed speeds studies have been performed to identify the relationship with accident rates. Operational speeds may be simplified into the demand of drivers over roadways. Historically, operational speed studies have been focused on the level of speeds inferring the bigger speeds may lead to more severe damages. On the other hand, hypothetically, it also has been assumed the variance of speeds may be correlated with accident rates. Therefore, studies over observed operational speeds and their variance have been performed. Solomon (1964), Anderson & Nilsson (1997), Davis (2002) shows that operational speed variances have close relationship with accidents rates. Therefore, two elements pertaining to operational speeds have become prevailing in terms of traffic accidents, that is, speeds and variance of speeds.

The concept of design speeds is originated backward to 1930's to permit the majority of drivers to operate uniformly at their desired speeds. However, it has been observed most drivers are not operating uniformly according to selected design speeds. This is why consistency of design of road highways emerges.

Consistency of highway design elements may be regarded as one type of capacity for a specific roadway. The consistency is generally realized in the form of reduction of design speeds.

Lots of studies worldwide have studied over consistency of highway design. The Interactive Highway Safety Design Model (IHSDM) in USA is known for its design

consistency module. IHSDM is a suite of software analysis tools for evaluating safety and operational effects of geometric design decisions on two-lane rural highways. This is released by FHWA. The design consistency module uses a speed-profile model that estimates 85^{th} percentile, free-flow, passenger vehicle speeds at each point along a roadway. On the other hand, Messer (1980) evaluated the design consistency based on driver workload. Driver workload can be defined as the time rate at which drivers must perform the driving task that changes continuously until it is completed. Over the driver workload, Krammes and Glascock (1992) criticized that evaluation with driver workload is too much subjective.

The Australian rural road design guide and European road design guides considered operational 85 percentile speeds rather design speeds for road design. This means there would be disparity between design speeds and operational speeds. The reasons they use the operating speeds is to give the designer greater chances of feedback on the initial decision about design speeds under the assumption that operating speed studies provide consistency design.

There are a lot of geometric features which is considered during roadway design process. Curve radius, longitudinal slope, sight distance, cross section may play the role of choosing driving speeds together or independently. If the level of influence is expressed in one simple equation, the relationship between safety and geometric features may looks more clear.

4. New Approach to Distribution of Capacity and Demand

In the present paper, based on the preceding studies, one new approach is proposed combining statistical reliability and highway design consistency. The example of the new expression is in Fig 6. The variance of speeds are over the lanes are independently presented and together calculated. Then using the theory of summing normal distributions, the total variance and average are calculated. Now the whole term is defined as the demand part having its own average and variance.

The highway design elements divided into three things such as longitudinal slope, radius, and cross slope assuming each of element has an adequate design speed estimated. If the longitudinal slope is a normal range of slope which is design guidelines generally describe that the range is 0-3% , the design speed is designated here 100km/h. For the radius, speed prediction equation could be applied as shown

Fig 5. Then the total variance and average are calculated. Now the whole term is defined as the capacity which has its own average and variance.

Fig 5 Speed estimation equations (TRB, NCHRP 502)

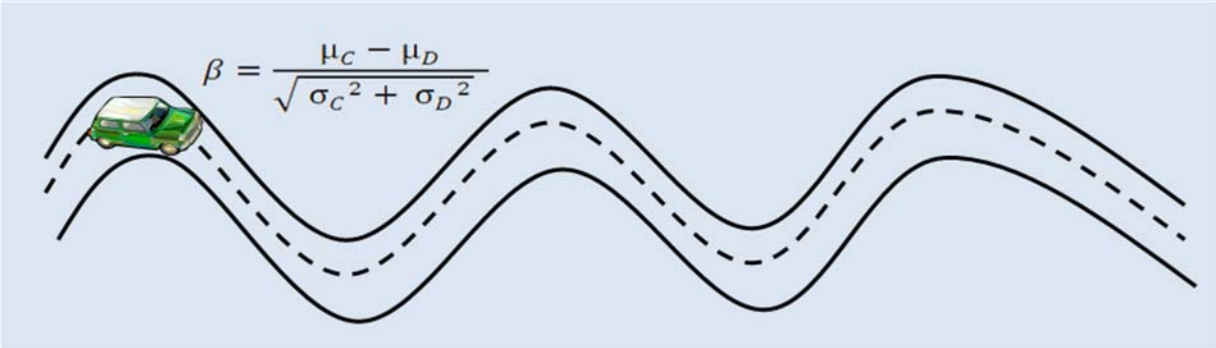
AC EQ (See note 1)	Alignment Condition	Equation (see note 2)	Num. Obser.	R^2	*MSE*
1.	Horizontal Curve on Grade: -9% ≤ G < -4%	$V_{85}=102.10-\frac{3077.13}{R}$	21	0.58	51.95
2.	Horizontal Curve on Grade: -4% ≤ G < 0%	$V_{85}=105.98-\frac{3709.90}{R}$	25	0.76	28.46
3.	Horizontal Curve on Grade: 0% ≤ G < 4%	$V_{85}=104.82-\frac{3574.51}{R}$	25	0.76	24.34
4.	Horizontal Curve on Grade: 4% ≤ G < 9%	$V_{85}=96.61-\frac{2752.19}{R}$	23	0.53	52.54
5.	Horizontal Curve Combined with Sag Vertical Curve	$V_{85}=105.32-\frac{3438.19}{R}$	25	0.92	10.47
6.	Horizontal Curve Combined with Non-Limited Sight Distance Crest Vertical Curve	(see note 3)	13	n/a	n/a
7.	Horizontal Curve Combined with Limited Sight Distance Crest Vertical Curve (i.e., K ≤ 43 m/%)	$V_{85}=103.24-\frac{3576.51}{R}$ (see note 4)	22	0.74	20.06

Finally, β could be obtained based on traffic demand and capacity. The value has meaning of safety margin. If design speeds are bigger than observed speeds, β is greater than zero representing the system with status safe.

If β is less than zero, the whole system could be regarded as one with unsafe conditions. This state occurs when the design speed is greater than the observed speed and more consolidated when the total variance is getting smaller. Now reliability indexes are calculated. Now, the value became the indicator the reliability of safety margin for a specific location.

Fig 6 Combination of statistical reliability and highway design consistency

	Observed Speed (demand)			Design Speed (capacity)			
Element	1st lane	2nd lane	total	Longi. slope	Radius	Cross slope	Total
Avg/Var	110	120	123/150	100	120	100	110/140



Conclusions

This paper is pertaining to how to apply the reliability theory to geometric design. The way of approach is in two folded. First is the evaluation of observed speeds lane by lane in terms of probability. The speeds are simultaneously evaluated based on variance. Second is the evaluation of design speeds based on design elements such as radius and cross slopes. Finally, the combination of two approaches is easily achieved using probabilistic reliability theory. The theory provides the relationship between demand and capacity relationship. This type of approach would serve to quantification of existing highway geometric deficiencies.

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